VULNERABILITY OF THE NETHERLANDS AND NORTHWEST EUROPE TO STORM DAMAGE UNDER CLIMATE CHANGE

A Model Approach Based on Storm Damage in the Netherlands

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Abstract. Storms occasionally bring havoc to Northwest Europe. At present, a single storm may cause damage of up to 7 billion U.S.$, of which a substantial part is insured. One scenario of climate change indicates that storm intensity in Northwest Europe could increase by 1–9% because of the doubling of CO_2 concentrations in the atmosphere. A geographic-explicit, statistical model, based on recent storms and storm damage data for the Netherlands, shows that an increase of 2% in wind intensity by the year 2015 could lead to a 50% increase in storm damage to houses and businesses. Only 20% of the increase is due to population and economic growth. A 6% increase could even triple the damage. A simpler model – based on national average data and combined with a stochastic storm generator – shows that the average annual damage could increase by 80% with a 2% increase in wind intensity. A 6% wind intensity increase could lead to an average annual damage increase of 500%. The damage in Northwest Europe is about a factor 6 higher than the damage in the Netherlands. Little potential seems to exist for reducing the vulnerability to storms in the Netherlands. More attention should be given to planning at the government level for disaster relief and to the development of coping strategies.

1. Introduction

The insurance industry was taken by surprise when Western Europe was hit by a series of winter storms with high economic losses in the late 1980s and early 1990s. Windstorm losses of over a few billion U.S.$ had been considered unlikely (Berz and Conrad, 1993). The winter storm of 1987 and the series of winter storms in 1990 proved different with estimated economic losses between U.S.$ 4 and 15 billion (valued at 1992 prices*). The January 1990 winter storm (Daria) alone caused economic losses of around U.S.$ 6.8 billion, of which U.S.$ 5.2 billion were insured (valued at 1992 prices) (Munich Re, 1993; Swiss Re, 1994; Dlugolecki, 1992). Total damages of Daria in the Netherlands are estimated at about Dfl. 2.6 billion (1990 values†), about 0.5% of Dutch GDP, of which Dfl. 1.5 billion (damage to private houses, businesses, industrial and commercial buildings and cars) was

* 1 Dfl. = 0.55 U.S.$ at 1992 values.
† 1 Dfl. = 0.49 U.S.$ at 1990 values

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TABLE I

Number and losses due to major world-wide wind storm events between 1960 and 1992 (Munich Re, 1993)[a]

	1960–1969	1970–1979	1980–1989	1983–1992	Rate of increase 80s/60s	’83–’92/60s
Number of windstorms	8.0	14.0	29.0	31.0	3.6	3.9
Economic loss (in U.S.$ billion)	22.6	33.6	38.0	88.1	1.7	3.9
Insured loss (in U.S.$ billion)	5.3	8.3	18.9	52.1	3.6	9.8

[a] ‘Major’ = cost greater than U.S.$ 500 million; damages are valued at 1992 prices and are corrected for inflation only.

covered by the insurance industry (Munich Re, 1993; Schraft et al., 1993; Dorland et al., 1999).

The total damages arising from these events seems high, but they are only a small proportion of the exposed property value. Thus, five years later hardly any traces of the 1990 storm events were left in Dutch society. Besides changes in building codes, little action has been taken to prevent future storm disasters in the Netherlands (Dorland et al., 1999). Mitchell et al. (1989) found a similar result when studying the October 1987 windstorm impacts in the United Kingdom. Thus, a developed society is not highly vulnerable to such an event and interest is therefore low.

However, figures published by Munich Re (1993) show that a dramatic change in the costs of severe storm events has taken place since 1960, see Table I. (Re)insurance companies take these increases seriously. They see the increasing losses as threatening for their profits and existence. The question has been raised whether these events are early signals of climate change. By studying and modelling past storm losses, they try to improve their understanding of the damage aspects of storms. Also, consultants, such as Applied Insurance Research and Risk Management Solutions, show great interest in modelling storm damage (Clark, 1986, 1991; Muir-Wood, 1996). Unfortunately, these models and the underlying data are not publicly available.

Forecasting storm damage is hampered not only by the limited empirical basis, but also by the high uncertainties of forecasting, particularly in the long term. Not only climatic changes and their impacts on extreme weather events, but also economic and demographic growth need to be forecast over a 25-year period, introducing large uncertainties. Even harder to predict is the way in which insurance companies will deal with the changing behavior of policy holders, which in itself is hard to foresee. Consequently, the analyses presented here are to be interpreted as what-if scenarios and vulnerability studies.

In this paper, two alternative models are presented which relate storm characteristics and storm losses to buildings in the Netherlands. The first model is more elaborate than the second. It is geographically explicit, focusing on the patterns of storm intensity and damage for a few recent storms. The second model investigates the annual average of aggregate damage, focusing on storm frequency and intensity. Using these models, the sensitivity of storm damage to variations in storm intensity is analysed by means of specific socio-economic scenarios. Next, policy options to influence the vulnerability to storminess are addressed. The paper starts with a review of the available literature on storms in Europe and storm forecasting.

2. Storm Literature Review

A number of studies of historic trends in storminess have been performed in the past decade by, amongst others, Hulme and Jones (1991), Isemer (1992), Palutikof et al. (1992, 1993), Ward (1992), Schinke (1993), Schmidt and von Storch (1993), von Storch et al. (1993), Kaas et al. (1996), Lambert (1996), Schmith et al. (1998), and the WASA group (1998). Lamb (1991) even produced a catalogue of severe storms for Northwestern Europe which extends back to the mid 1500s.

Particularly from the more recent studies of storminess throughout the twentieth century, a consensus opinion is gradually beginning to emerge. This suggests, first, that variability on decadal time scales is a clear feature of storminess over the last hundred years (e.g., Schmith et al., 1998), second, that there is no clear trend in the number or severity of storms throughout this whole period (e.g., WASA group, 1998), and, finally, that the period since about 1970 until present has seen a steep increase in storminess (e.g., Lambert, 1996). More tentatively, this increase is not identified as a product of global warming, but more likely as a function of the decadal-scale natural variability. Similar levels of storm intensity were seen at the beginning of this century (WASA group, 1998).

Although the frequency of storm occurrence and severity over Europe in the past few years remains within the bounds of natural variability, the extent of storm damage has increased over the past decades. According to Berz and Conrad (1993), the reasons for the increase in storm damage are:

- increase in population density, particularly in vulnerable areas;
- increase in wealth;
- increase in insurance;
- more complex and vulnerable production and living;
- higher propensity to claim; and
- environmental changes.

In some cases, for example in Florida, building standards have not always been implemented to their full extent in recent years (Dlugolecki et al., 1996). This also causes damages to increase. However, this is not the case in the Netherlands.

Insurance premiums have increased and deductibles have been introduced in many countries in recent years. This was a reaction to an increase in the commission of re-insurance companies who in turn reacted, with references to climate change, to the series of heavy losses in the late 80s and early 90s. In the Netherlands, deductibles of 0.1% of the value of property (with a minimum of Dfl. 150 and a maximum of Dfl. 500) were introduced after the high storm losses in early 1990.

This raises the basic question: 'What can be expected for the future intensity of extra-tropical storms in Northwest Europe?'.

Predictions of future changes in the intensity and/or frequency of storms over the North Atlantic and Western Europe due to the enhanced greenhouse effect are based on model simulations of future climate. A number of studies have been made, with conflicting results. Simulations by the U.K. Hadley Centre generally suggest an intensification and poleward shift of cyclone tracks over the North Atlantic and Western Europe (Hall et al., 1994; Carnell et al., 1996). In contrast, experiments with the Canadian Climate Centre second generation model (Lambert, 1995) and with the Community Climate Model (Zhang and Wang, 1997) both suggest a reduction in storm activity over Europe. Beersma et al. (1997) found little change in response to a doubling of atmospheric CO_2 concentrations.

These storm track analyses do not always provide useful guidance on the potential for changes in storminess over specific land areas. Palutikof and Downing (1994) constructed geographically-detailed scenarios of the change in wind speed over Northwestern Europe, based on results from the Hadley Centre transient response climate model experiment reported by Murphy (1992). These scenarios show an increase in the mean wind speed over the next 75 years, in the range of 1–9%, with a best estimate of +6%. This figure compares well with the 7% increase in winter mean wind speed by the 2050s suggested by the CCIRG (1996) scenario for southern England. These results suggest an increase of storm frequency and/or severity, and Palutikof and Downing assume a *pro rata* increase in the maximum gust speed over the same period. This is, in fact, a conservative assumption (Katz and Brown, 1992). Although such scenarios must be regarded as a plausible future rather than as a prediction, they serve to guide our thinking on the likely range of change. For the purposes of the discussion in this paper, a 2% increase in storm intensity over the next 25 years is held conceivable on the basis of this evidence.

In the next sections, scenarios for individual storm losses in the Netherlands in 2015, and scenarios for the average damage in the Netherlands and Northwest Europe until 2065, partly based on the studies mentioned above, are given.

3. Specific Storm Losses in the Netherlands in 2015

It is possible to estimate future damage due to a specific storm event for a given set of socio-economic scenarios. The storm damage model used, the socio-economic scenarios and the forecasted insured storm losses, for a range of increase in storm intensity, are described below.

3.1. A STORM-DAMAGE MODEL FOR THE NETHERLANDS

The storm damage model for the Netherlands is based on five storm events between 1987 and 1992. For model construction, data on the two-digit postal level were obtained. For each storm, data on insurance of private houses and businesses from the Centre for Insurance Statistics (CVS) include:

- the number of policies affected,
- the average loss sustained, and
- the deductibles (i.e., the amount of loss to be covered by the policyholder prior to any payment by the insurers).

For private houses, only the damage to the buildings is included. For businesses, an unknown proportion of the policies also includes insurance of building contents. Data from the Royal Dutch Meteorological Office (KNMI) include:

- the hourly maximum gust speed, and
- the hourly mean wind speed

for 30 meteorological stations. Then, for each year and for each postal code area, data from the Dutch Postal Service (PTT) and the Central Bureau for Statistics (CBS) include:

- the number of houses and businesses,
- the average income per household, and
- the geographical area.

The average income per household was introduced as a proxy for the average value of the houses and/or insured sum. The actual values or the insured value were not available for this study.

Storm intensity (maximum gust speed, $\hat{V}_{\max}$, and maximum hourly mean wind speed, $\bar{V}_{\max}$) and storm duration maps were derived by distance-related weighted spatial interpolation between the measurement sites. The wind data so derived were again aggregated to the level of the storm damage data, i.e., the two-digit postal code level, by (arithmetically) averaging over the grids in postal code areas. This results in values for $\hat{V}_{\max}$, $\bar{V}_{\max}$, and storm duration (D) for every postal code area i and every storm event t. This interpolation and the aggregation were carried out with the geographical information system SPANS (cf. SPANS, 1993).

In interpolating the wind and gust speed data, no allowance was made for differences in topography and surface roughness length. Both of these factors are important determinants of spatial variations in near-surface hourly mean wind speeds (Cook, 1985). However, topography is in general an insignificant feature of the physical landscape of the Netherlands, and can be ignored. Surface roughness variations should be taken into account, but the data were not readily available for this project. Note that in the final model equation (Equation (1)), the wind predictor is, in fact, the maximum gust speed rather than the hourly mean wind speed. For this variable, surface roughness length is much less important. As Deacon (1955) pointed out, 'strong gusts during storms are the result of the descent of relatively large bodies of air carrying with them a high wind speed from aloft', and as such they maintain their store of momentum because of their relatively small ratio of surface to volume (Wieringa, 1976; Ashcroft, 1994).

First, the area-specific data on the number of houses and businesses and the postal code area were tested for correlations. Only low and statistically non-significant correlations were found. The plots of the observed damage to houses and businesses to the maximum gust speed for the five storms are presented in Figure 1.

Second, the variables were tested for their importance in the explanation of the damage. For these tests, square, cubic, and exponential relations of the wind speed parameters to the damage were analysed. All these types of relations have been described in the literature (including Cook, 1985; Christofides et al., 1992; Schraft et al., 1993). The test results indicated that storm duration and the average income per household should not be included in the function. Apparently, average income is not a good proxy for the value of houses or for the average insured sum. Furthermore, the exponential relation is statistically preferred over the square and cubic relations (see Dorland and Tol, 1995, for a further discussion). The plots of the log total damage to the maximum gust speed are presented in Figure 2.

Third, the remaining variables in the exponential function were tested for parameter stability over different areas in the Netherlands (North versus South, East versus West, and the Building Standard code areas) and building density ranges. No improvements in the model were found. This might indicate that the building standards for the different regions in the Netherlands, which are based on the probabilities of occurrence and extent of maximum gust speeds in different areas, cancel out regional differences.

Fourth, the remaining variables in the exponential function were tested for stability over the individual storms and wind speed ranges. The wind speed parameter was found to be unstable in the model for private houses, i.e., its relationship to damage varied over different ranges of wind speed. This may be due to the limited number of observations. Testing the model fitted to all five storms against individual storms shows a preference for the latter for private houses. However, in none of these cases did the wind speed parameter reveal an identifiable pattern. In addition, estimating the wind speed parameter for four storms yields sufficiently

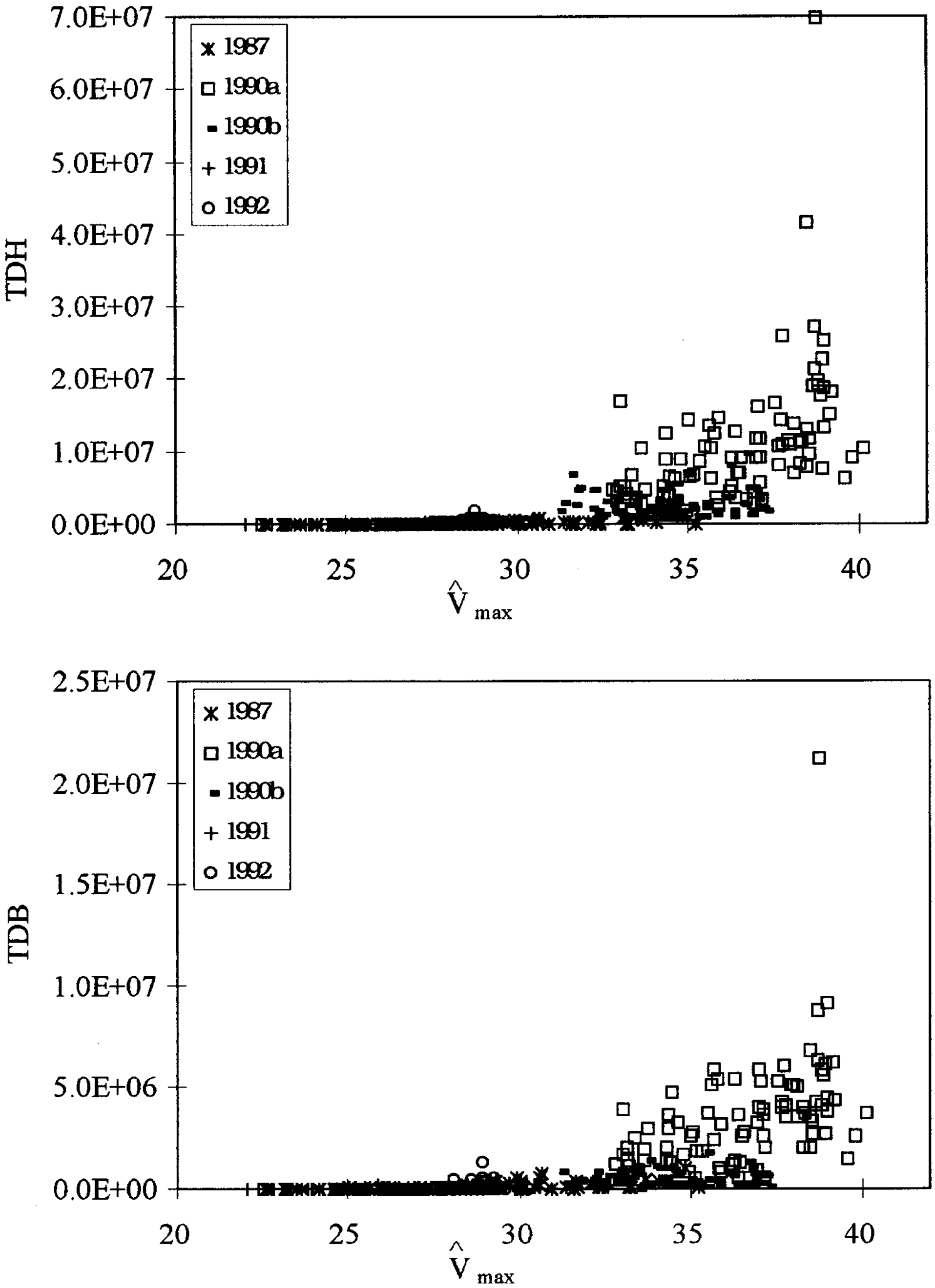

Figure 1. Observed damage to houses – TDH – (above) and businesses – TDB – (below) in Dfl. to observed maximum gust speed (in m/s) for the five storm events in each of the 90 postal code areas.

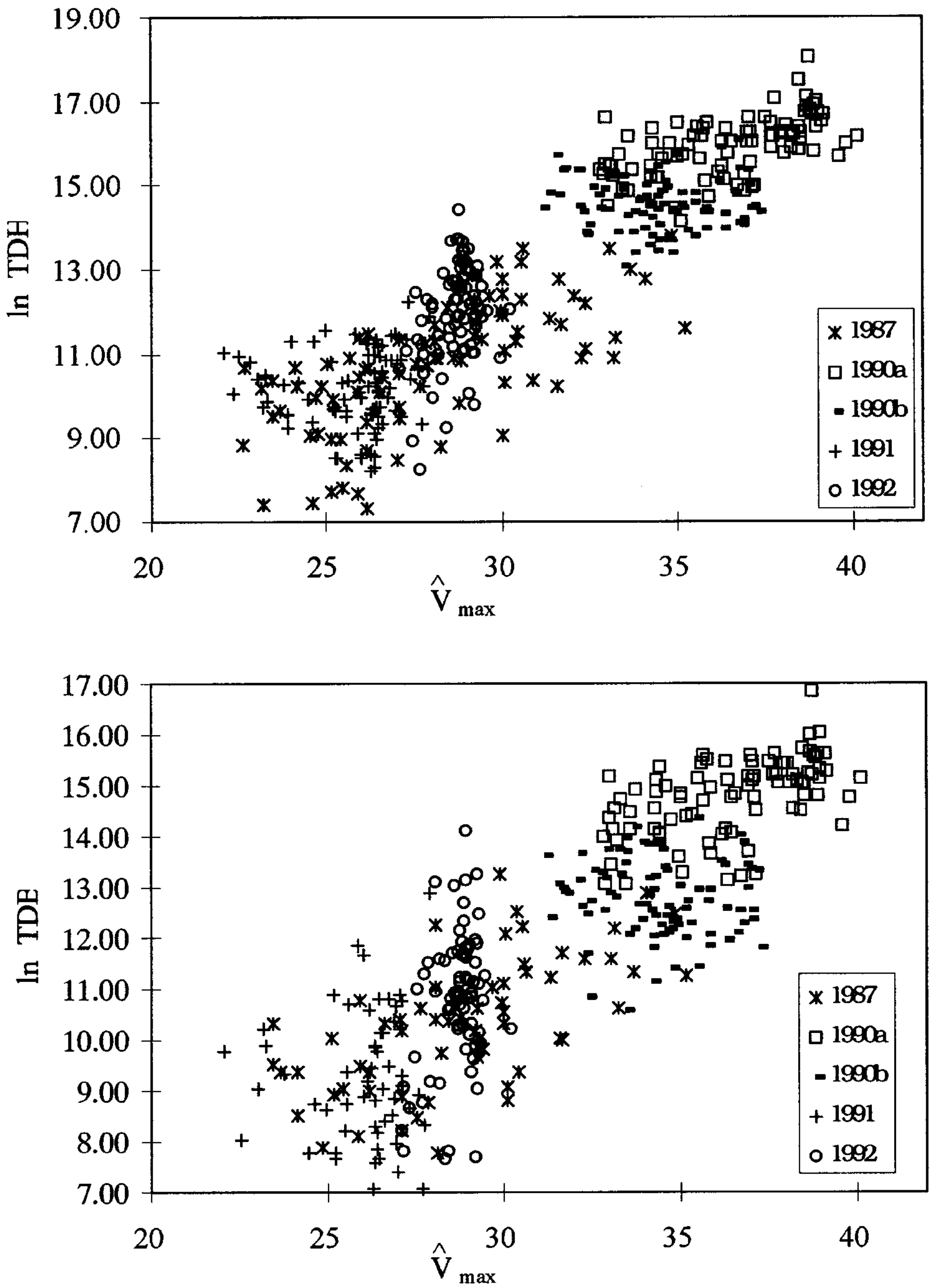

Figure 2. Logarithm of observed damage to houses – TDH – (above) and businesses – TDB – (below) in Dfl. to observed maximum gust speed (in m/s) for the five storm events in each of the 90 postal code areas.

TABLE II

Estimated parameter values of the exponential relation between storm damage to private houses or businesses and storm intensity (the standard deviation is given in brackets)

Dataset		Private houses	Businesses
Number of observations		436	367
Parameters			
C	Estimate	–14.4 (1.2)	10.0 (1.3)
	t-Statistic	–11.9	–7.6
α	Estimate	0.93 (0.09)	0.58 (0.10)
	t-Statistic	11.0	5.7
β	Estimate	0.26 (0.08)	0.42 (0.10)
	t-Statistic	3.3	4.4
χ	Estimate	0.50 (0.01)	0.46 (0.01)
	t-Statistic	47.2	32.6
R^2		0.84	0.75
Loglikelihood		–611	–566
Sum of squared residuals		421.2	471.3
F-statistic		763.8	356.5

reliable predictions for the fifth. Therefore, one and the same function should be used for all storms and the entire domain of the explanatory variables (see Dorland and Tol (1995) for a further discussion).

The final model is shown in Equation (1). The parameters are displayed in Table II.

$$\ln \mathrm{TDO}_{i,t} = \alpha \ln O_{i,t} + \beta \ln A_{i,t} + \chi \ln \hat{V}_{\max;i,t} + c \,, \tag{1}$$

where:

$\mathrm{TDO}_{i,t}$ = total damage to objects (houses or businesses) in area i for storm event t (in Dutch guilders);
$O_{i,t}$ = number of objects (houses or businesses) in area i for storm event t;
$A_{i,t}$ = postal code area i for storm event t (in km^2);
$\hat{V}_{\max;i,t}$ = storm input data in area i for storm event t (in m/s);
c = constant;
α, β, χ = coefficients;
i = postal code area number (10, 11, ..., 99); and
t = storm event number (1, 2, ..., 5).

TABLE III

Modelled and observed storm damage to private houses and businesses in the Netherlands (Dfl. million). Twice the standard deviation of the parameter estimates is given in brackets

Year of storm	1987	1990	1990	1991	1992
Month and date of storm	October 15–17	January 25–26	February 25–March 1	December 22–24	November 25–27
Storm event number	1	2	3	4	5
Total damage to private houses:					
Modelled	21 (12)	903 (286)	214 (57)	3.3 (0.9)	12 (3)
Observed	10	977	232	3.3	22
Modelled-observed	11	–74	–18	0	–10
Total damage to businesses:					
Modelled	6.8 (4.1)	202 (66)	59 (17)	1.3 (0.4)	4.3 (1.2)
Observed	4.1	310	42	1.5	8.2
Modelled-observed	2.7	–98	17	–0.2	–3.9

The model was finally evaluated by comparing calculated and observed damage as shown in Table III. The 95% confidence interval of the calculated mean damage is indicated in brackets, assuming the damage has a normal distribution.

Although the model may not hold for every individual storm, it gives a reasonable estimation of the average damage due to a storm in a given year. Better functions can only be derived by analysing more storm events, which enables the inclusion of more variables. Variables which could then be included are meteorological (e.g., storm duration and wet and dry conditions) and physiographical (e.g., surface roughness) variables and possibly a better proxy for the value of property. However, including more than three variables, with the available limited dataset, would lead to overfitting, resulting in a meaningless model.

3.2. SOCIO-ECONOMIC SCENARIOS

The growth in the number of houses and businesses for each postal code area must be known in order to forecast future storm losses. Four long-term scenarios for population and economic growth rates in Europe have been defined by the Central Planning Bureau in the Netherlands (CPB, 1992). They are presented in Table IV. These scenarios are used to predict the growth in the number of houses and businesses, respectively. It is assumed that the growth rates in the Netherlands are equal to the growth rates in Europe and that the growth rates are equal for all postal code

TABLE IV

Population and economic growth rate scenarios for Europe (CPB, 1992)

Nr.	Name	Population growth rate in Europe	Economic growth rate in Europe
1.	Global shift	0.4%	1.9%
2.	European Renaissance	0.3%	2.8%
3.	Global crisis	0.4%	2.0%
4.	Balanced growth	0.3%	3.2%

areas in the Netherlands. In addition, we define a 'No Change' scenario for which it is assumed there will be no change in the number of houses and businesses. This scenario is used as a reference case only. The scenarios probably give conservative damage growth rates as the increase in the value of property is not accounted for. Furthermore, a significant increase in the insurance density in the Netherlands is not foreseen as insurance is, at present, nearly universal. Only state property is not insured.

3.3. STORM LOSS FORECASTS

The future storm scenarios for this analysis are based on the severe storm of January 1990 in the Netherlands with an increase in the modelled gust speeds ($\hat{V}_{\text{max}}$) of between 0 and 10% (Dorland and Tol, 1995). In other words, the future storms are spatially identical to the January 1990 storm, but more fierce. The January 1990 storm was selected since this storm event was one of the worst storms in the Netherlands in the past 100 years, bringing with it very high economic losses. It affected the highest populated areas in the country, and 55% of the housing stock of the Netherlands was exposed to gust speeds of 37 m/s or higher (Dorland and Tol, 1995).

The exponential relationship between wind speed and damage is not valid at wind speeds far beyond the calibration range, since the damage curve must flatten off once most buildings have been hit. The maximum damage is, of course, reached when all buildings are completely destroyed. Increasing wind speeds by up to 10% beyond the calibration range, as here, is expected to remain within the range of the exponential relationship, and should not lead to a large overestimation of the damage. The total damages due to the January 1990 event were only a small percentage of the total stock at risk (the total damage was 0.5% of GDP). Furthermore, only between 5 and 18% of all houses and businesses sustained damage and the average sustained damage was 1,000–2,000 Dutch Guilders for houses and 2,000–

TABLE V

Relation between the mean damage to private houses and businesses in 2015 in the Netherlands for the different socio-economic scenarios and a 0 to 10% increase in the wind intensity. Twice the standard deviation is given in brackets. The figures are given in Dfl. million at 1990 values

Socio-economic scenario	Percentage increase in the wind intensity					
	0	2	4	6	8	10
Private houses						
No change	903	1322	1937	2838	4158	6094
	(286)	(421)	(620)	(918)	(1346)	(1983)
Global shift/global crisis	991	1451	2125	3114	4563	6687
	(314)	(462)	(680)	(1000)	(1476)	(2176)
European Renaissance/	968	1418	2077	3043	4458	6534
Balanced growth	(307)	(451)	(665)	(979)	(1443)	(2156)
Business						
No change	202	287	407	578	820	1164
	(66)	(94)	(135)	(192)	(275)	(393)
Global shift	266	377	535	759	1077	1529
	(87)	(124)	(177)	(253)	(361)	(516)
Global crisis	270	382	543	770	1093	1551
	(88)	(126)	(180)	(257)	(367)	(524)
European-Renaissance	302	428	608	862	1224	1737
	(99)	(141)	(202)	(288)	(411)	(587)
Balanced growth	319	453	643	912	1295	1838
	(105)	(149)	(213)	(305)	(435)	(622)

14,000 Dutch Guilders for businesses, which is only minor damage compared to the average sum insured per property.

Table V and Figure 3 present the results of the analysis under the socio-economic scenarios and the storm-damage model presented above.

According to Buth (1995, pers. comm.) and Staalduinen (1995, pers. comm.), statistical evidence that recent changes in the Building Standards for the Netherlands have led to a decrease in damage is not available. They argue that the trend towards using lighter building materials might even lead to an increase in the vulnerability of structures to wind. Therefore, no correction for changes in the vulnerability of buildings has been made in this analysis. Furthermore, the coefficient of variation of damage is assumed to be independent of both the level of wind intensity and building density. This assumption was tested and not rejected (Dorland and Tol, 1995).

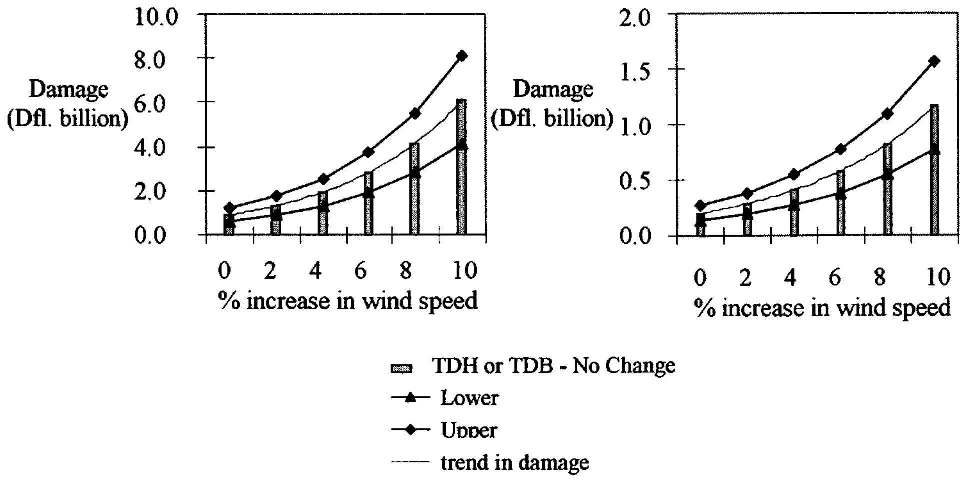

Figure 3. Scenario results for the damage to private houses (left panel) and businesses (right panel) in 2015 in the Netherlands (1990 values).

The results show that damage risks are very sensitive to the intensities of future storms, but the damages under the different CPB growth scenarios are not statistically different. Thus, if a 2% increase in storm intensity is held conceivable in the next 25 years, the insured losses to houses and businesses would increase by 50% for both private houses and businesses. Other effects of storms, e.g., casualties, damages to building contents, and especially losses from business interruption, are also likely to increase. However, such damages were not included in this analysis.

4. Average Damage in the Netherlands and Northwest Europe

The previous section focused on specific storms with a geographically-explicit wind and damage pattern. This allowed us to study the vulnerability to variations in Daria-like storms. Daria is only one storm, however. Equally interesting is an analysis of annual mean storm damage and how that may be affected by climate change. Obviously, the five storms analysed by the specific storm damage model yield little information on the average. Given the inescapable problems with data quality and availability, the analysis here has to step back from a geographically explicit analysis and examine aggregate damage instead. Consequently, storm intensity must also be reduced to a single index. Below, a storm model for the Netherlands is built and extrapolated to Northwest Europe.

TABLE VI

Heavy winter storms over land in the Netherlands since 1910 (Wieringa, 1990)

Nr.	Year	Day/month	Intensity		
			$\bar{V}_{max}$[a]		$\hat{V}_{max}$[b]
			Bf	m/s	m/s
1	1911	30/9–1/10	11	30	38
2	1912	27/8	10	27	41
3	1914	28/12–29/12	11	32	42
4	1916	13/1	10	27	42
5	1921	6/11	11	32	45
6	1925	9/2–10/2	10	27	39
7	1926	9/10–10/10	10	26	35
8	1928	16/11–17/11	11	29	38
9	1928	23/11	10	25	38
10	1928	25/11	10	28	37
11	1938	4/10	10	26	38
12	1940	13/11–14/11	10	26	38
13	1943	7/4–8/4	11	31	35
14	1944	7/9	12	34	–
15	1949	1/3–2/3	11	29	39
16	1953	31/1–1/2	10	27	40
17	1960	20/1	10	26	41
18	1967	17/10	10	27	40
19	1972	13/11	11	29	42
20	1973	2/4	11	30	43
21	1976	2/1–3/1	11	30	41
22	1983	1/2	10	27	38
23	1983	27/11	10	27	40
24	1984	14/1	10	27	37
25	1987	16/10	10	27	41
26	1990	25/1–26/1	11	29	44
27	1990	3/2–4/2	10	24[c]	34[c]
28	1990	25/2–27/2	10	26	41
29	1990	28/2–1/3	10	24	35[c]

[a] $\bar{V}_{max}$ = highest measured hourly mean wind speed.
[b] $\hat{V}_{max}$ = highest measured gust speed.
[c] Estimated values from Swiss Re (1993).

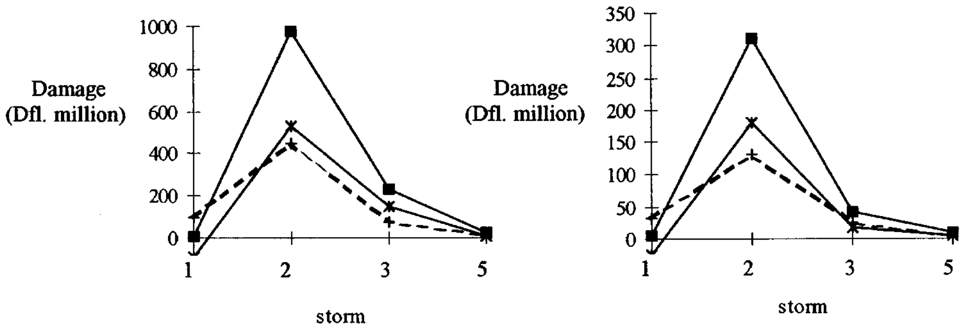

Figure 4. Damage to private houses (left panel) and businesses (right panel) in million Dfl. as observed (filled squares) and as modelled (dashed line). The residuals (asterisks) are also displayed.

4.1. AN ALTERNATIVE STORM MODEL FOR THE NETHERLANDS

Table VI displays the Dutch storm history of the 20th century. Twenty-nine storms affected the country between 1910 and 1990; that is, on average, 0.36 storms per year. This KNMI record contains data on both the storm frequency and the storm intensity. It is used to calibrate the storm model.

Annual mean maximum gust speed is calculated with the stochastic weather generator (using Monte-Carlo simulation) fitted to the data of Table VI. The weather generator is a double stochastic process: A Poisson process is used to generate the number of storms per year and a Pareto IV process is used to generate the intensity of the storm (see Tol, 1996b). Thus, it is a numerical device which produces artificial weather with statistical characteristics similar to the observed weather.

The database to estimate a storm damage function is rather poor. We only have the four observations on total damage to houses and business mentioned in Section 3.1 (the 1991 event is not a storm according to the Beaufort scale). These damage data need to be related to the maximum gust speed.

The models estimated for the four storms are:

$$\mathrm{TDH} = 2.48\ 10^{-7}\ e^{0.48\hat{V}_{\max}}; \quad \mathrm{TDB} = 1.49\ 10^{-7}\ e^{0.46\hat{V}_{\max}}, \tag{2}$$

where TDH and TDB are the total damage (in Dfl. millions) to houses and businesses, respectively. The parameters are, of course, highly uncertain, but the central estimates are reassuringly close to those found for the detailed model presented above. Figure 4 depicts the observed and modelled damages. Unfortunately, no data were available for an independent validation.

TABLE VII
Average annual storm damage in the Netherlands (in Dfl. million)

Year	Average			Daria (modelled)
	Private houses	Businesses	Total	total
1990[a]	34	10	44	1,100
‘2015’[b]	61	18	79	1,600
‘2065’[c]	219	59	278	3,400

[a] Average over 100,000 random realisations from a stochastic storm generator coupled to a storm damage model, both fitted to historical data.
[b] Two percent increase in modal wind speed; no change in vulnerability.
[c] Six percent increase in modal wind speed; no change in vulnerability.

4.2. ANNUAL MEAN STORM DAMAGE IN THE NETHERLANDS

Given the stochastic storm generator and the storm damage model (valid for the early nineties only), it is possible to calculate the expected annual storm damage in 1990. Table VII displays the results. The expected damage is calculated from 100,000 replications of the year 1990. Average annual damage is Dfl. 44 million. This estimate is too uncertain to derive a confidence interval. The maximum annual damage over the sample of 100,000 replications is Dfl. 17 billion. This maximum is, of course, arbitrary. It is an estimate of the impact of a ‘very rare’ storm. Daria costed about Dfl. 1.3 billion. The wind gusts measured during Daria have return periods of 1 to 80 years, depending on the location. In areas with the highest population densities, return periods are about 30 years. So, Daria is not very rare. Comparison of the ‘maximum’ damage according to the model and the damage due to Daria suggests that the model is not overextrapolating.

The storm generator can be readily altered to produce a hypothetical future climate: Coupled to the damage model, the impact of such a change on the present socio-economic situation can then be calculated. Sensitivity analyses reported by Dorland and Tol (1995) reveal that the estimates are highly uncertain. Table VII displays the average and maximum annual storm damage for a 2% (‘2015’) and 6% (‘2065’) increase in modal wind speed. For a 2% increase, the wind damage increases by about 80%; for a 6% increase, damage rises more than 500%. The increase is larger than the increase in damage due to a Daria-like storm, where a 6% increase in wind speed would lead to a 300% increase in damage. The increase in average damage is therefore largely due to a more frequent occurrence of severe storms.

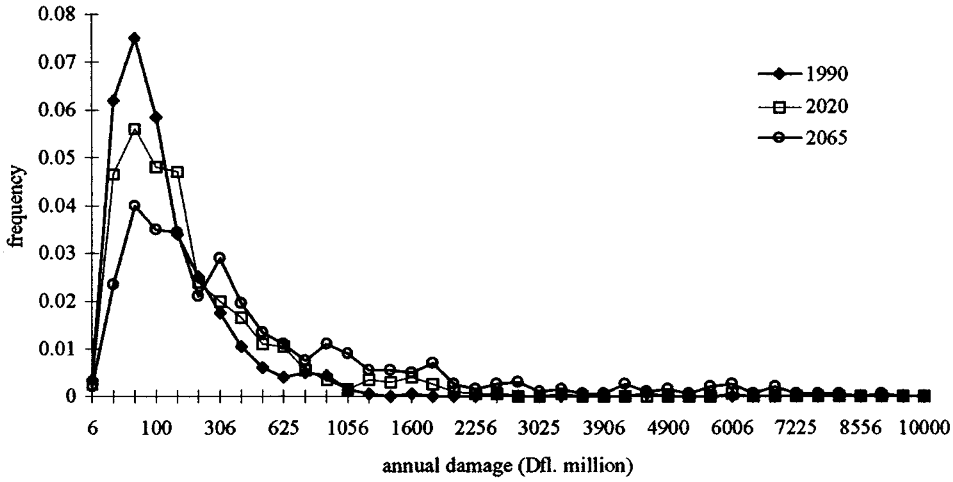

Figure 5. Probability density function of the annual storm damage, based on 1,000 replications of the model, for the current situation ('1990') and increases in model wind speed of 2% ('2015') and 6% ('2065'). The x-axis is on a quadratic scale.

Figure 5 depicts the corresponding damage distributions. The figure illustrates the tremendous variability of storminess over the Netherlands.

Figure 6 displays the average storm damage over a period of 101 years. Modal wind speed rises from the 1990 value to 106% of that after 75 years. For comparison, the damage under constant risk and under rising storm frequency (same assumptions as intensity) are also displayed. The smooth line in Figure 6 is the best-fitting quadratic function: $\Delta\mathrm{TD} = 42.5\Delta\hat{V}^2_{\mathrm{max}}$. Assuming that modal wind speed increases 2.4 m/s (6%) for a global mean temperature rise of 2.5 °C, the damage cost function would be $\Delta\mathrm{TD} = 38.1\Delta\mathrm{GMT}^2$.

4.3. AVERAGE STORM DAMAGE IN WESTERN EUROPE

The Netherlands is but one country, and not the largest in the world. It would be interesting to know the impact of climate change on larger regions, such as Northwest Europe. At this stage, only some crude estimates can be made. Further analysis is planned.

The Munich Re (1993) study contains some data on storm losses in Northwest Europe, i.e., Austria, Belgium, Denmark, France, Germany, Great Britain, Luxembourg, Scandinavia, Switzerland, and the Netherlands. The data comprise the eight storms in 1990. Regressing European losses on Dutch losses leads to a regression coefficient of 6.8 with a standard deviation of 1.1 for insured losses (R^2 of 77%) and a regression coefficient of 6.2 with a standard deviation of 1.2 for total economic losses (R^2 of 62%).

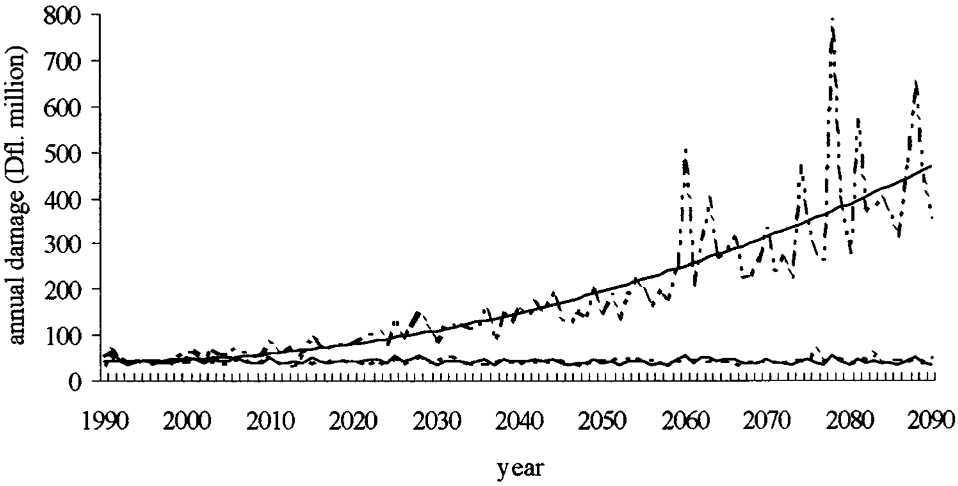

Figure 6. Average annual damage for constant storm risk, a scenario in which modal wind speed increases linearly to 106% of the 1990 value over 75 years, and a scenario in which storm frequency increases linearly to 106% of the 1990 value over 75 years. Average annual damages under constant storm risk and under increasing storm frequency are hardly distinguishable. Averages are for 1,000 replications.

Thus, it is roughly estimated that the impact in absolute terms of changes in storm intensity will be 6–7 times as large in Northwest Europe as in the Netherlands.

5. Policy Options

Which policy options are available to challenge this vulnerability to future storm losses? A distinction can be made between three types of disaster management policy: Preparedness, protection, and prevention (Tol, 1996a). The following sections discuss the first two of these options for storms in the Netherlands. The third is not considered feasible as this would mean changing weather and climate. Potential increases in storm damage, however, are an argument for limiting anthropogenic climate change by reducing greenhouse gas emissions.

5.1. PREPAREDNESS

Preparedness includes insurance, entitlements to government relief, early warning systems, etc.; that is, the socio-economic coping mechanisms to absorb and nullify the consequences of a disaster. With this definition in mind, an extensive literature search was carried out to assess what the policy responses to the Daria event were, if any. It appeared that only in a few sectors was analysis, let alone action, undertaken.

The Dutch Railway Company *Nederlandse Spoorwegen* was heavily criticised for providing inadequate information to stranded travellers during the 1990 storm events (COT, 1990). They produced a report with recommendations about how to manage such an event in future (NS, 1990). However, since the power supply is through overhead wires, the railway system will remain highly susceptible to storm. The *Bosschap*, an association of forest owners, developed a calamity plan on managing storm risks in their forests (Bosschap, 1993). Further analysis is required to determine if this plan can be implemented in the forestry sector as a whole. Adopting the plan will, of course, not prevent trees from being blown down, but it could reduce the social, economic, and ecological impacts of storms. The Crisis Research Team (COT, 1990), an official team installed to evaluate large scale disasters in the Netherlands, concluded in 1990 that local, provincial, and national governments could be better prepared for large scale disasters. They advised that the role of the media in disaster situations should be nationally regulated. People also have to be made aware that warnings and advice given should be taken seriously. Thus, more attention should be given to 'social relief' strategies. It is questionable, however, whether the Dutch society can decrease insured storm damages by being better prepared (nearly all property in the Netherlands is insured). From the Munich Re (1993) study, it could be concluded that re-insurance companies may in the future seek for ways to withdraw from a broad coverage of sustained damage, even though governments would be certain to discourage or even forbid such actions (Dlugolecki et al., 1996).

5.2. PROTECTION

Protection is the structural part of coping. Protection strengthens or shields the stock at risk so that less damage is sustained.

In the Netherlands, the vulnerability of buildings to storms is reduced by setting building standards. However, in this storm damage analysis, no traceable effect of building codes was found, see Section 3. This may be due to the crudeness of our method, an even vulnerability of houses and businesses over the Netherlands or the small influence of building standards on the damages. The national government triggered adjustments to building standards after the severe storms in 1990. In the new regulations (NEN 6702, 1993), buildings should be able to withstand higher wind speeds. The building industry embraced these adjustments in order to improve its image.

As in the U.K. (BRE, 1991), the damages in the 1990 storm events were mainly to roof tiles and timber fences, which are also insured in the Netherlands.

The Hail Insurance Company *Hagelunie* monopolizes the market for insuring greenhouses in the Netherlands. They analysed the causes of the high damages in this sector extensively and demanded technological adjustments for decreasing storm damage after the 1990 events (Staalduinen, personal communication).

However, the influence of these and other protection policies on storm damage in the Netherlands is not known. Until now, almost no research has been done to evaluate these types of impact management.

6. Conclusions

In order to estimate damage from future storms in the Netherlands, which under climate change might be more severe, two storm-damage models have been developed by statistically analysing the meteorological characteristics and insurance claims of five storms in the period 1987–1992.

The first model is a geographically explicit storm damage model linking meteorological and damage data on a two-digit postal code level for the Netherlands. This model confirms that future storm risks (to private houses and business) are very sensitive to maximum wind speed, much more than to likely socio-economic developments. Scenario analysis with this geographically explicit storm model shows that if the Daria event would repeat itself in the year 2015, with a 2% increase in wind speeds due to climate change, the damages would be around 50% higher than they were in 1990.

The second model is a stochastic weather generator (using Monte-Carlo simulation) coupled to aggregated damage data for the whole of the Netherlands. Scenario analysis with this 'average damage' model indicates that the annual mean insured damages could, due to the above-mentioned climate change, increase by 80% in 25 years (the year 2015). Furthermore, it is estimated that the annual mean damages in Northwest Europe as a whole could be around 6 to 7 times as large as the damages in the Netherlands.

However, the extent of climate changes and their influence on maximum gust speeds, which drive the damages in these models, is still highly uncertain, although a 2% increase in the maximum gust speed in 25 years is held conceivable. Scenario analyses performed with these models are very speculative for three reasons. First, climate change uncertainties are large. Second, the models draw on limited databases of storm characteristics and storm damage. Third, the behavior of insurance companies, policyholders, and governments are hard to predict and therefore not included in the models. Even though there is little knowledge of how climate will change storm intensity, frequency, and tracks, it can be concluded from this study that storm damage is highly sensitive to climatic changes.

Little potential seems to exist for reducing storm vulnerability in the Netherlands. (Re)insurers look for options other than preparedness, protection, and adaptation to minimise their losses, such as withdrawal from broad coverage. However, it is unlikely that governments will permit the widespread adoption of such a strategy. More attention should be given to planning for disaster relief at central and local government levels and to the development of coping strategies.

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